# Development of high average power Nd:YAG laser system using the SBS-phase conjugation mirror.


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# Overview of phase conjugation

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The discovery of the early 1970 by Zel'dovich et al.

**Optical phase conjugation is now established as a domain of nonlinear optics**

**The SBS(stimulated Brillouin scattering) as effective phase conjugator can be performed with stable operation for improving the beam quality of high-average-power lasers.**

# Contents

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**The possibility have been investigated that the SBS materials could be used as a phase conjugator for high power lasers.**

(1) Introduction

(2) Experimental results

(a) High energy operation SBS PCM in FC-75

(b) High power Nd:YAG laser system with SBS-PCM for JT-60U Thomson scattering diagnostics.

(c) A single-stage diode-pumped Nd:YAG amplifier system at a 1 kilohertz-repetition-rate using a SBS-PCM.

(d) SBS-PCM by circulation of a coolant liquid for high average laser system (5kW;1J, 5kHz)

(3) Conclusion

# Several nonlinear materials.

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## (1) Optical Kerr effects
## (2) Stimulated Brillouin scattering

(a) Pulse operation
(b) Fast risetime (a few ns)
(c) High energy and high power operation

The interest in the development of high-energy or high-average power laser sources

## (3) Photorefraction
## (4) Free carries in semiconductors
## (5) Saturable amplifications
## (6) Saturable absorption
## (7) Thermal gratings

# The capability of liquid SBS-PCM demonstrate up to 1 kW of output power while keeping the near-diffraction beam quality.

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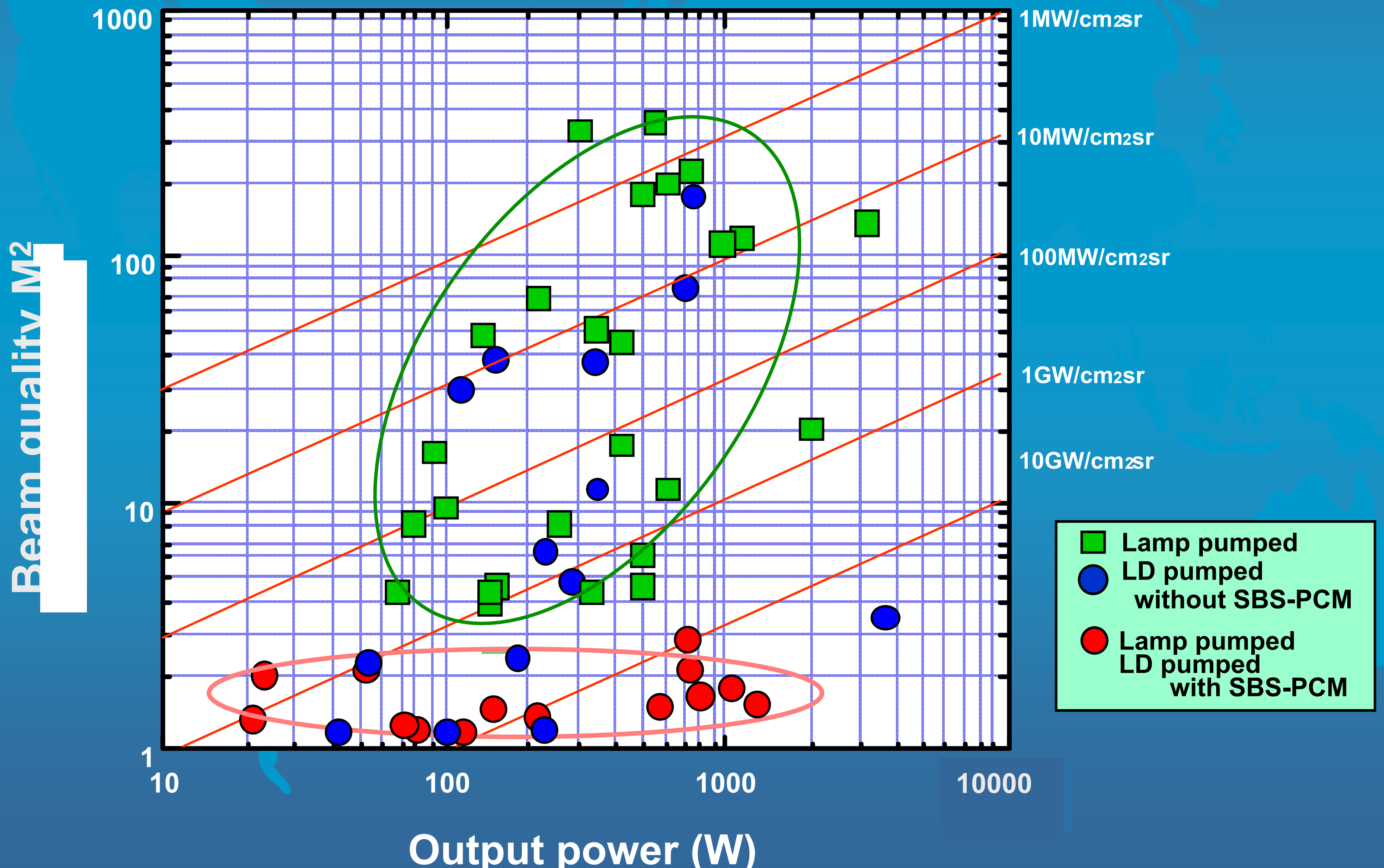
The stimulated Brillouin scattering-phase conjugation mirror (SBS-PCM) is a useful tool for improving the beam quality of high-power laser systems.



# High power laser development require new optical technology.

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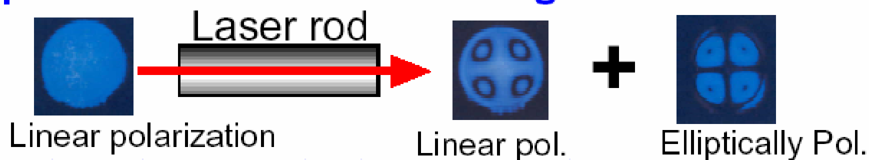
| Problems of a high power laser development | Advantage of SBS-PCM |
|---|---|
| (1) Wave front distortion by thermal effect; Thermal lens effect; Depolarization due to birefringence; (2) Growth rate of distortion (B-factor) by non-linear refractive index (Limitation of output power) | Compensation of the wave front distortion (Producing a high quality beam) |
| (3) Precise alignment | Alignment free |
| (4) Parasitic oscillation due to ASE — ASE(Amplified Spontaneous Emission) | Rejection of ASE due to SBS threshold |
| (6) Diffraction at the edge | Spatial filtering effect |

## (1) Wave front distortion by thermal effect

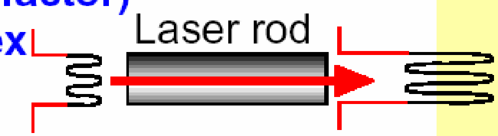
**Thermal lens effect**


**Depolarization due to birefringence**

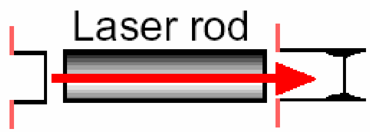



## (2) Growth rate of distortion (B-factor) by non-linear refractive index

(Limitation of output power)




## (6) Diffraction at the edge



# Parameters of some useful SBS liquids

"PHASE CONJUGATE LASER OPTICS"2003, JOHN WILEY & SONIC, INC

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| Liquids | Wavelength $\lambda$ (nm) | Index n | Density $\rho$ (g/cm$^3$) | Gain coefficient $g_B$ (cm/GW) | Relaxation time $t_B$ (ns) | Bandwidth $\Delta\upsilon_B$(MHz) | Brillouin Shift $\upsilon^B$ (GHz) |
|---|---|---|---|---|---|---|---|
| $GeCl_4$ | 1064 | 1.46 | 1.87 | 12.0 | 2.3 | 69.2 | 2.10 |
| $SnCl_4$ | 1064 | 1.36 | 2.33 | 11.0 | 1.8 | 182.0 | 2.20 |
| $PCl_4$ | 1064 | | 1.57 | 8.6 | | | 2.76 |
| $SiCl_4$ | 1064 | 1.41 | 1.48 | 10.0 | | | 2.17 |
| $TiCl_4$ | 1064 | 1.61 | 1.73 | 14.0 | 1.5 | 108.3 | 3.00 |
| $CCl_4$ | 1064 | 1.46 | 1.59 | 3.8 | 0.6 | 265.3 | 2.76 |
| $H_2O$ | 694 | 1.33 | 1.00 | 4.8 | 0.5 | 317.0 | 5.91 |
| $CH_4O$(Methanol) | 532 | 1.33 | 0.79 | 13.7 | 0.4 | 334.0 | 5.40 |
| $C_2H_6O$(Ethanol) | 694 | 1.36 | 0.79 | 12.0 | 0.5 | 353.0 | 4.55 |
| n-Pentane | 532 | 1.36 | 0.63 | 18.0 | 0.7 | 230.0 | 5.31 |
| n-Hexane | 532 | 1.38 | 0.66 | 16.6 | 0.7 | 238.0 | 5.76 |
| n-Heptane | 532 | 1.39 | 0.68 | 12.6 | 0.7 | 230.0 | 6.10 |
| n-Octane | 532 | 1.40 | 0.70 | 12.6 | 0.5 | 312.0 | 6.36 |
| $CS_2$ | 1064 | 1.60 | 1.27 | 60-130 | 6.4 | 24.8 | 3.76 |
| Acetone | 1064 | 1.36 | 0.79 | 20.0 | 2.0 | 79.6 | 2.67 |
| Freon-113 | 1064 | 1.36 | 1.58 | 6.2 | 0.8 | 189.0 | 1.74 |
| FC-72 | 1064 | 1.20 | 1.68 | 6.5 | 1.2 | 270.0 | 1.10 |
| FC-75 | 1064 | 1.30 | 1.77 | 5.0 | 0.9 | 350.0 | 1.34 |

Low absorption and high damage at 1$\mu$m

: $Cl_4$ group, Freon group

# FC-75 SBS-PCM shows high reflectivity against high energy YAG laser input.

ILE Osaka Univ.

H.Yoshida et al. Applied Optics, Vol.36, No.16(1997)3739.

## SBS material

**Liquid fluorocarbon (Fliorinert FC75)**

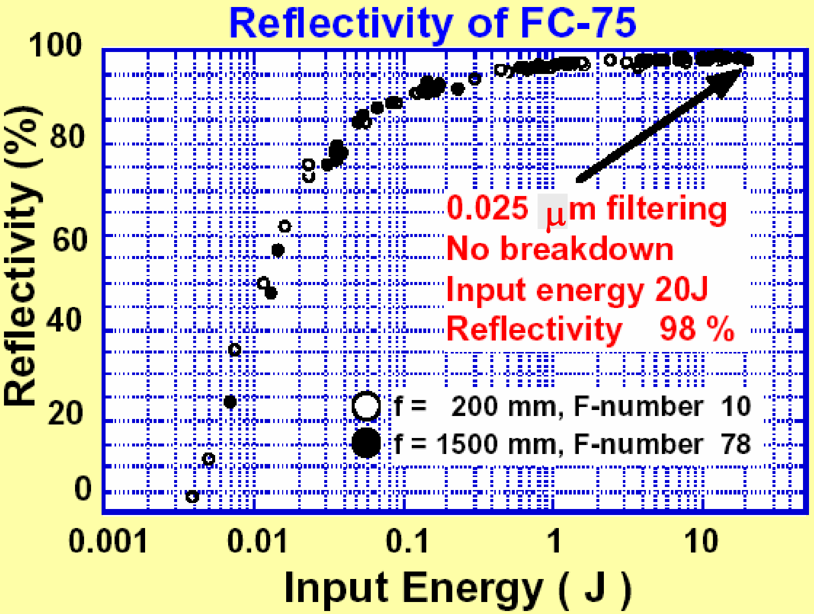
(1) Low absorption at laser wavelength
($\alpha < 1\times10^{-6\sim7}$/cm)

(2) No impurities/micro particles
Precise cleaning & filtering

(3) High damage threshold
suppression of laser breakdown
(>100 GW/cm$^2$ @1 ns)

(4) Fast relaxation of accoustic wave
less than laser rising time
(0.9 ns @1.06 µm)

(5) High SBS gain for lower threshold
(7 cm/GW @1.06µm)




## Laser performance

**Note that single mode laser with a band width narrower than SBS band width is necessary to get high reflectivity.**

# High reflectivity over 95% is achieved on high-energy and high-repetition operation

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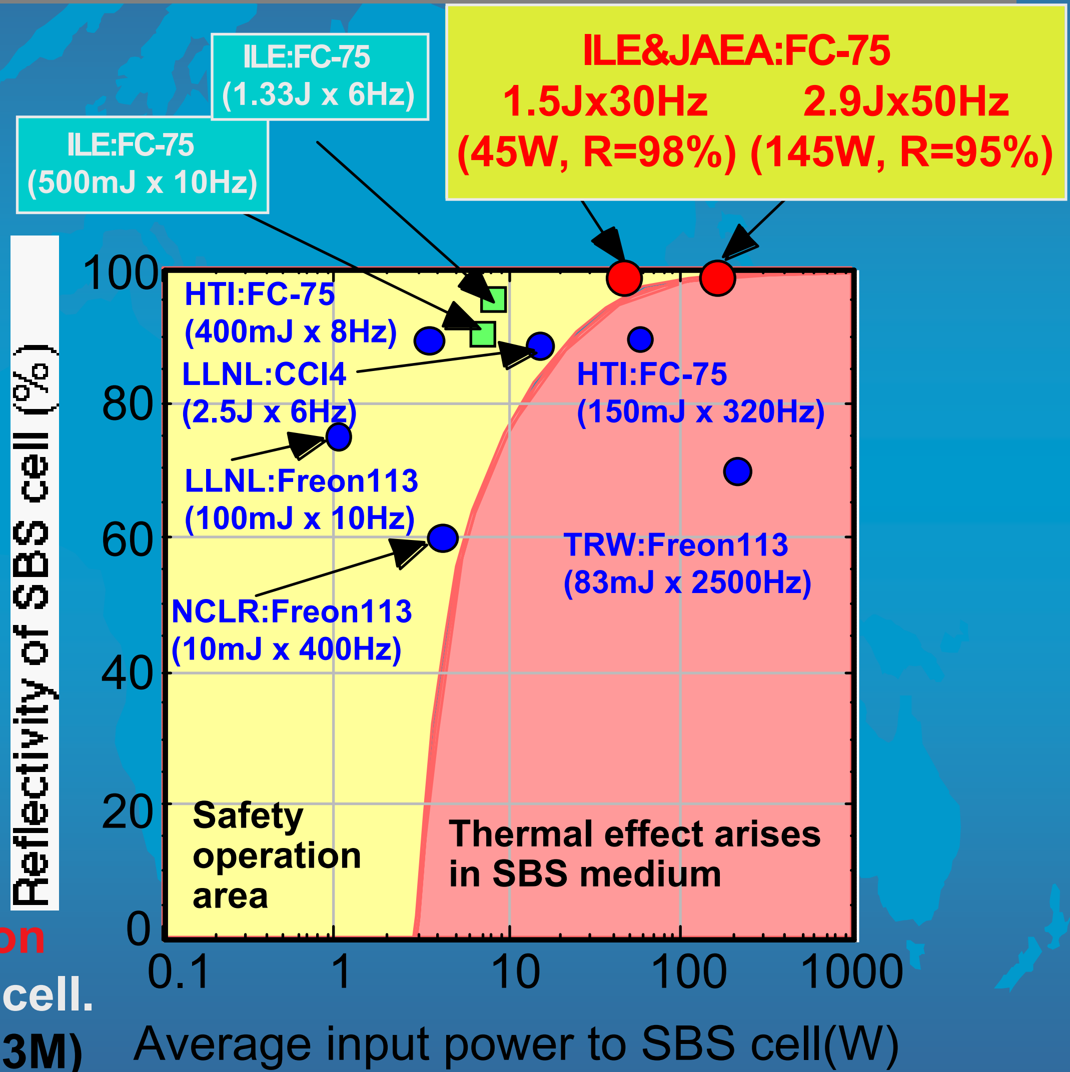
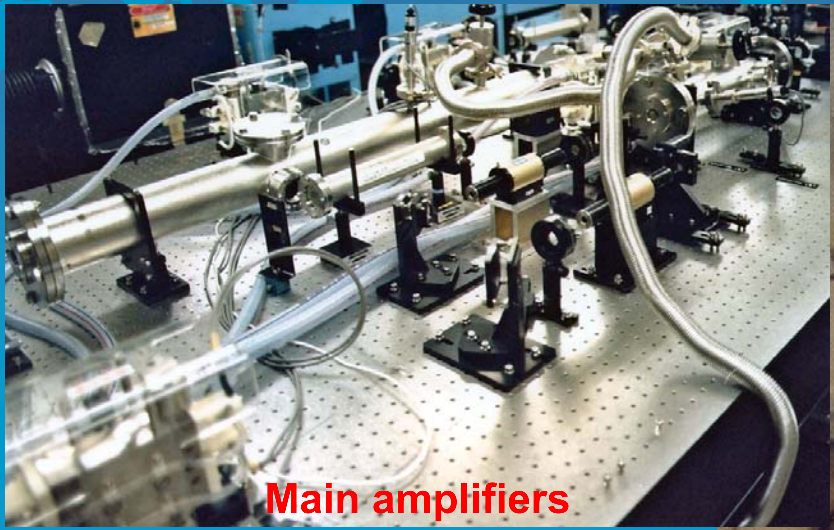


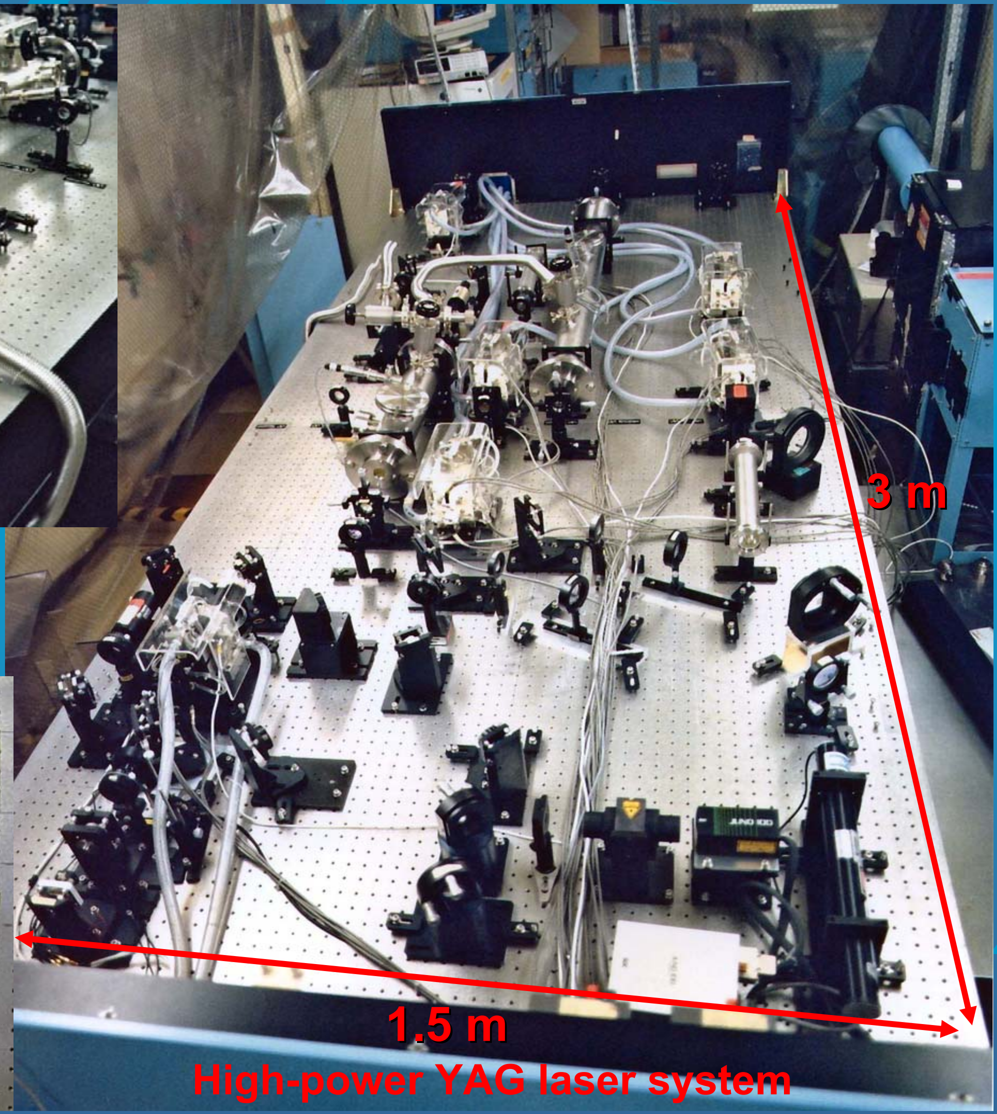

Precise filtered heavy fluorocarbon liquid is filled in a stainless steel cell.
(Fluorinert FC-75; Trade name of 3M)

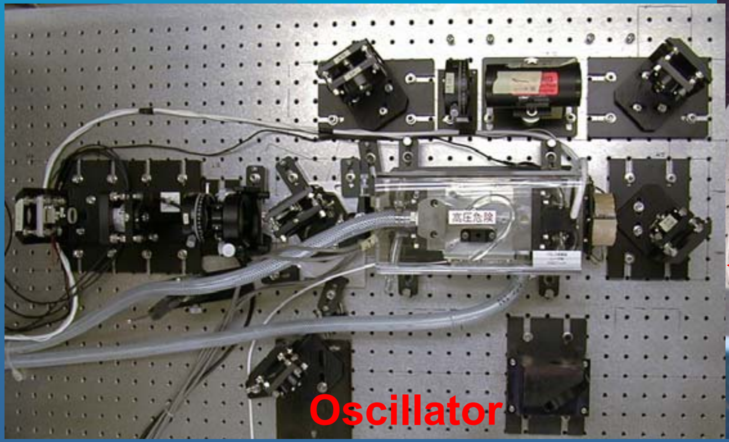
# High power Nd:YAG laser system with SBS-PCM for JT-60U Thomson scattering diagnostics.

ILE Osaka Univ.

H.Yoshida et al. J. J. A. P, No.42(2003)439.



# Optical layout of high-power Nd:YAG laser system.

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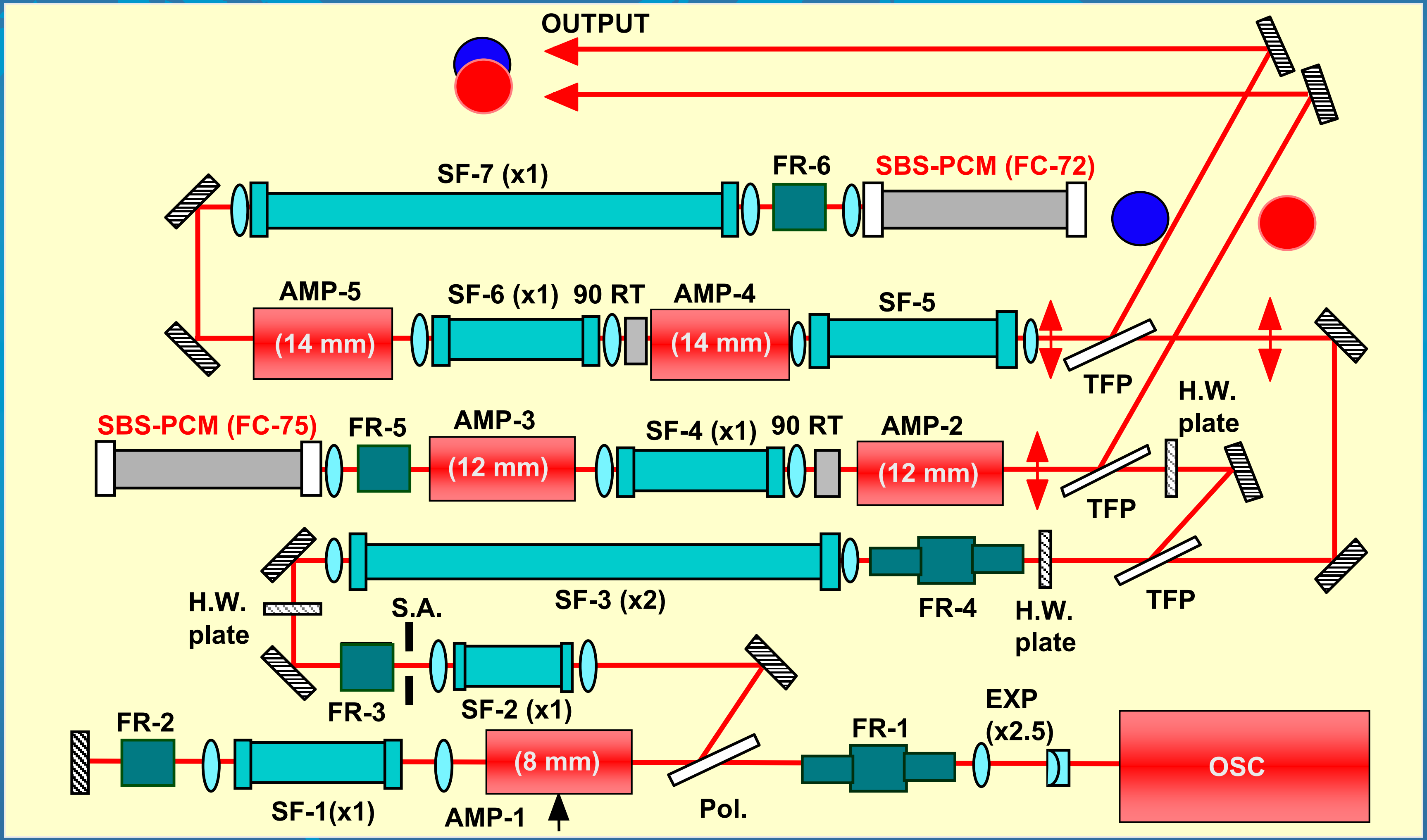
(1) H.Yoshida et al. J. J. A. P, No.43(2004)1038. (2) T. Hatae et al. J. Plasma Fus. Res. 80(2004)870.




Amp, Nd:YAG amplifier; SF, spatial filter; FR, Faraday rotator; TFP, thin-film polarizer; HWP, half-wave plate; 90 RT, 90-degree rotator; and SBS-PCM, SBS phase conjugation mirror.

# Beam qualities of high-power Nd:YAG laser system.

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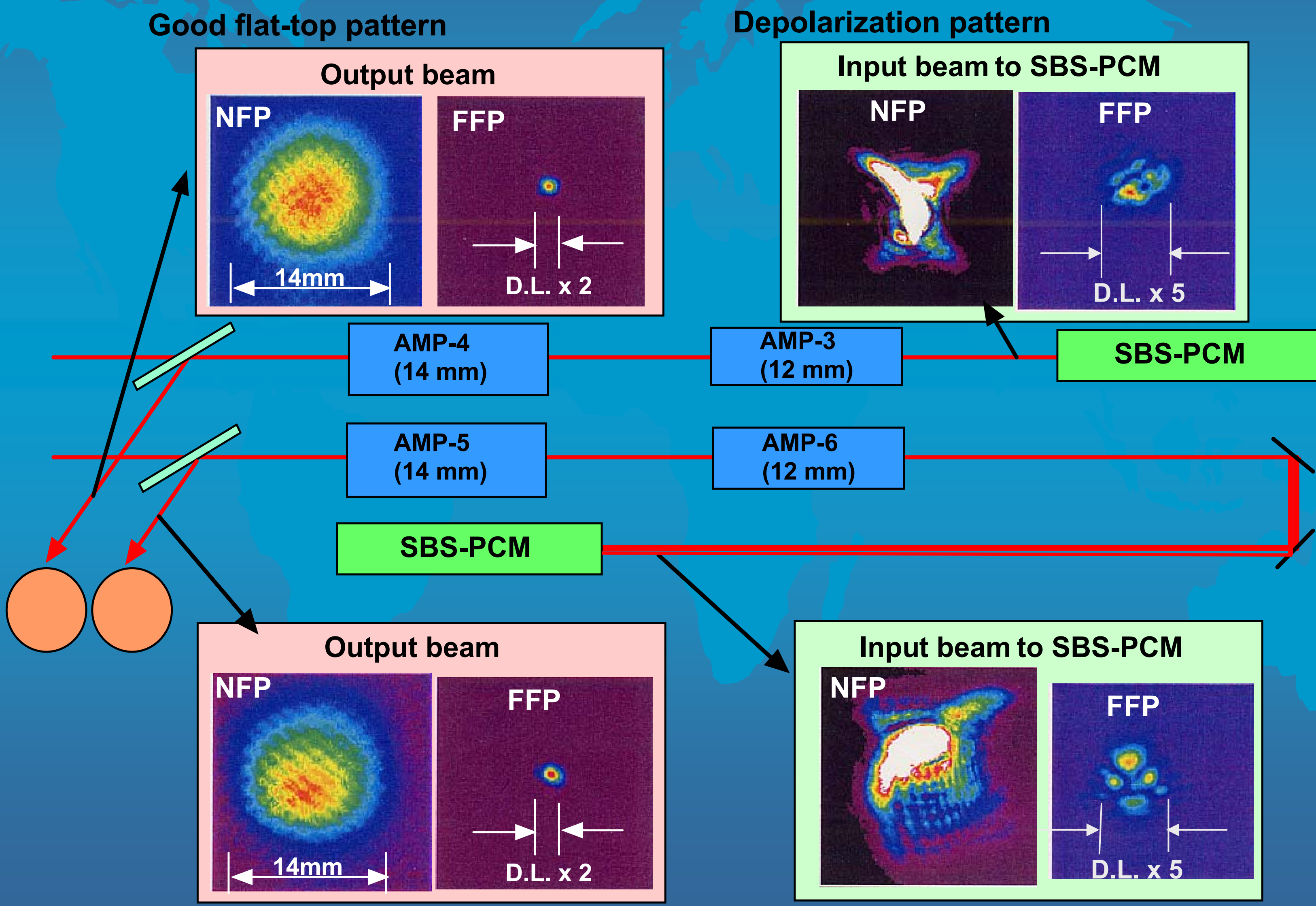
The near-field and far-field patterns of the double-pass amplified pulse with SBS-PCM.



# Beam quality (far-field patterns).

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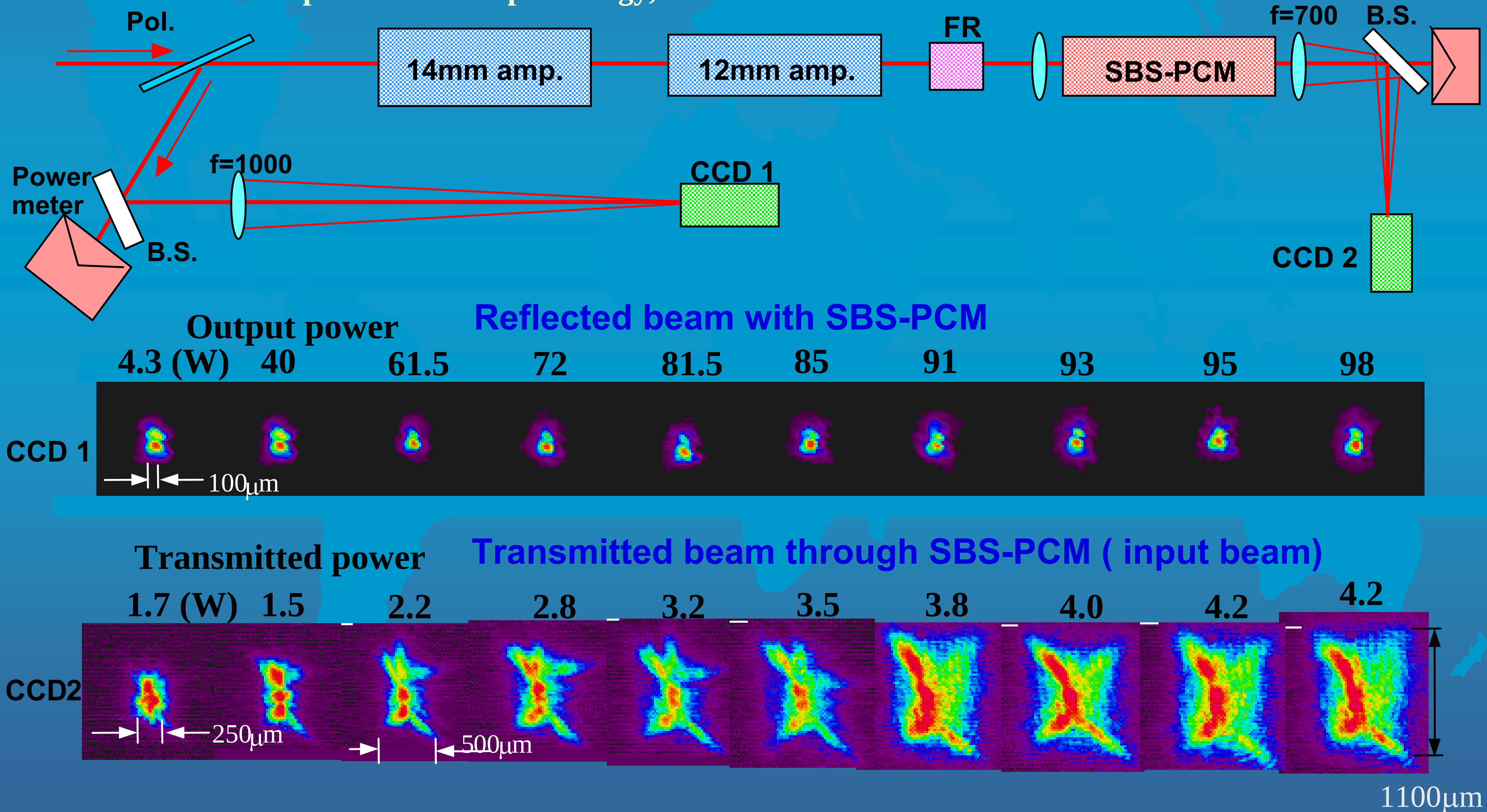
The spot size of the single-pass amplified beam was incresed to a full angle divergence ten-fold the diffraction-limited value.

On the other hand, the spot size of the reflected beam with SBS-PCM not depend on the output energy, and constant



# Interference effect is sucessfully suppressed by a time-lag and a difference of frequency.

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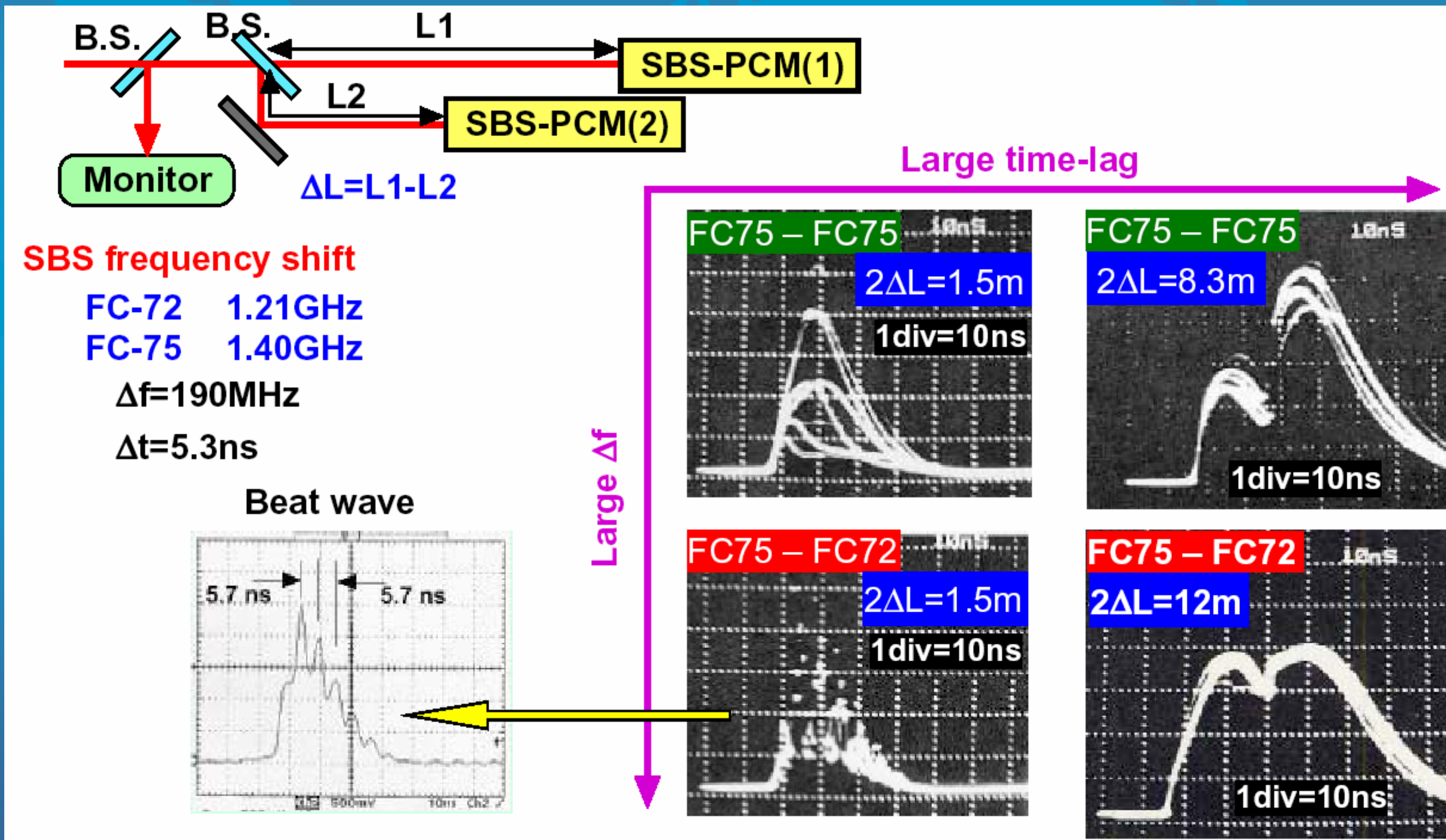
Stability of pulse shape when two beams were combined into one beam with a given separation of optical path between beams and a combination of different SBS materials.



## The maximum input power to the SBS cell was about 75 W at 50-Hz operation without degradation of the reflecting laser beam.

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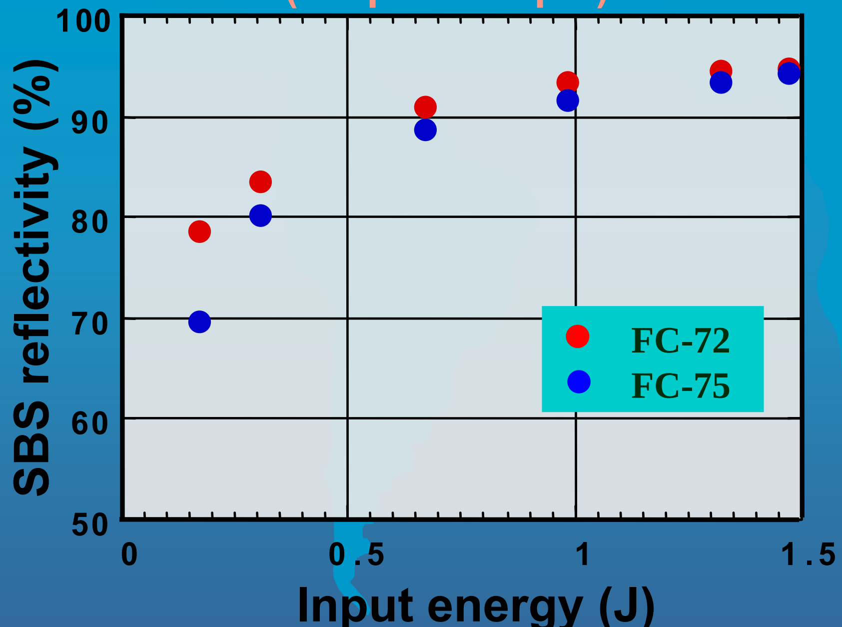
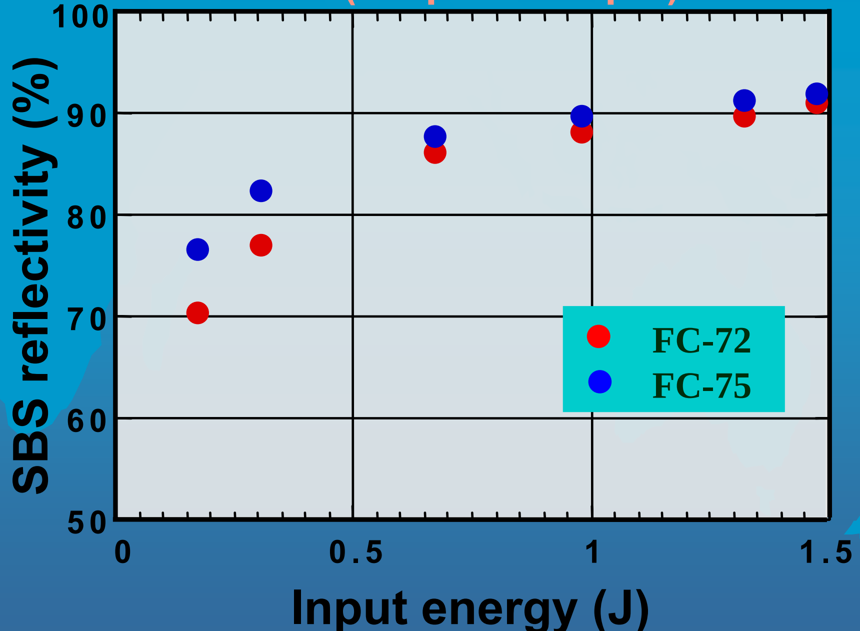
The SBS threshold energy of FC-72 was reduced than that of FC-75 because of higher SBS gain coefficient. A maximum intrinsic SBS reflectivity of approximately 95% was obtained at over 1.5-J incident energy.

| | | |
|---|---|---|
| Operation condition | Maximum input power | 75 W |
| | Maximum input energy | 1.5J |
| | Repetition rate | 50Hz |

Optical length L=1.62m (Amp.3 +Amp.4)




Optical length L=5.87m (Amp.5 + Amp.6)



# 373 W output energy achieved in each chain with various configurations and total amplified output energy of a double-pass amplifier with the SBS-PCM.

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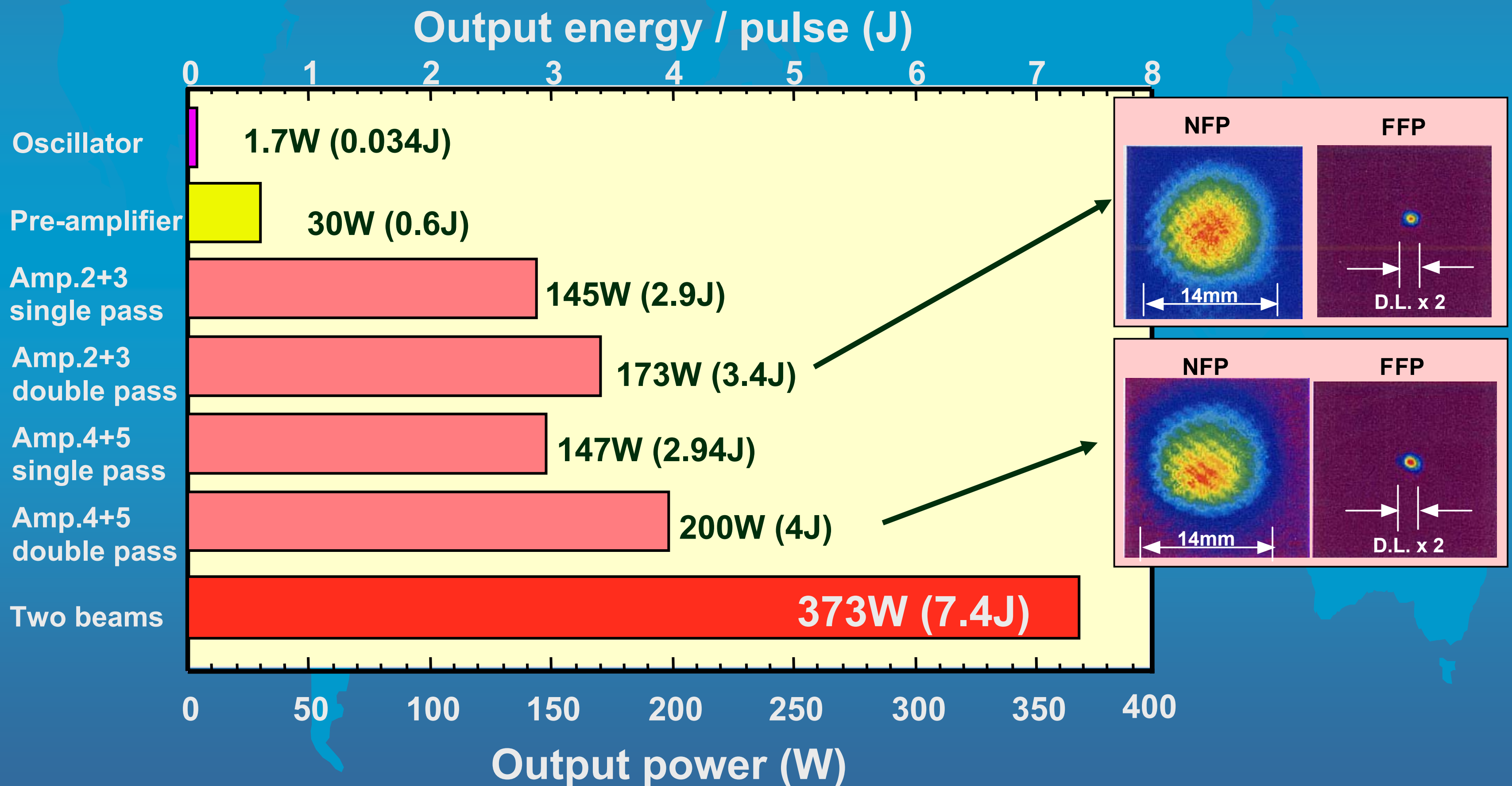
**SBS effect shows good near-field pattern and far-field pattern of double-pass-amplified output beam.**



# The averaged laser power was increased by a factor of 8

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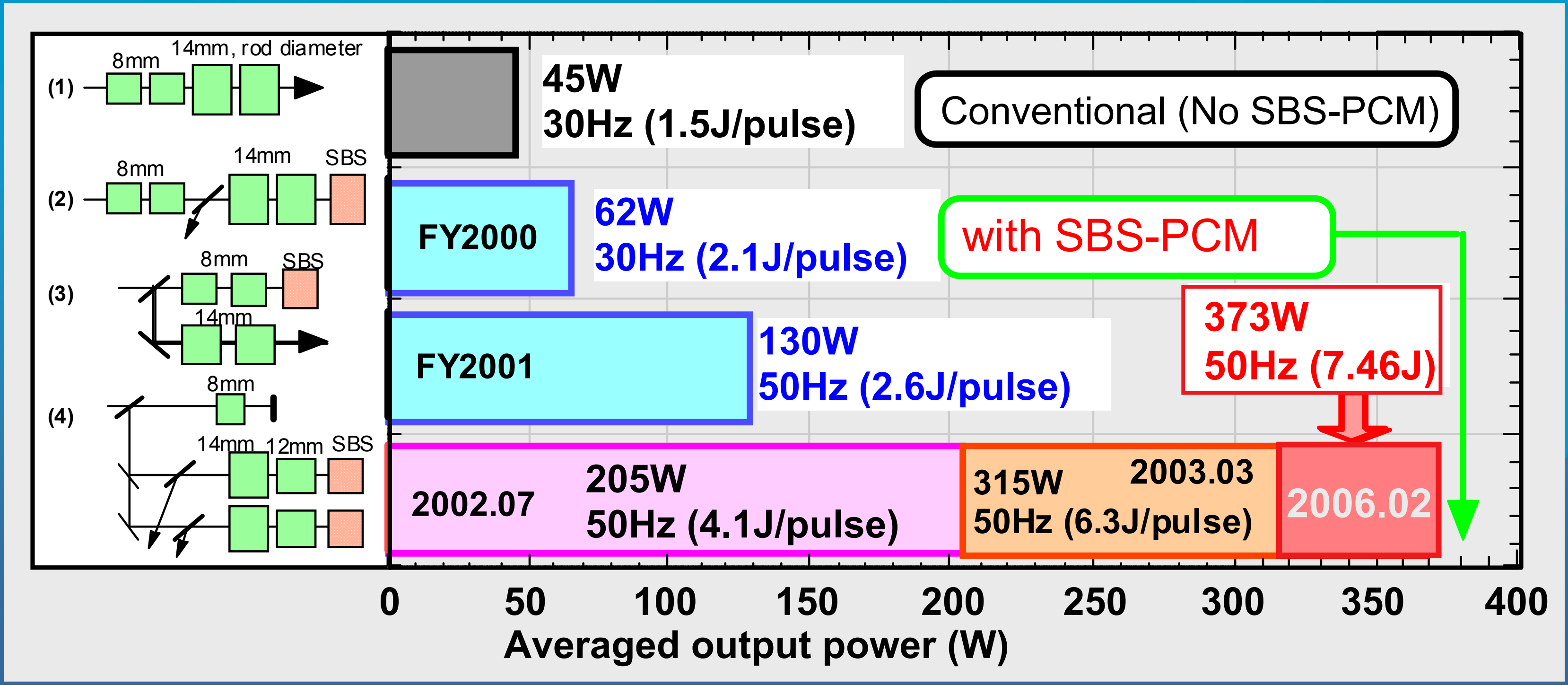
- To improve the measurement performance by increasing actual laser
- power, SBS-PCM have been introduced into YAG laser system in JT-60.
- Rearrangement of YAG laser amplifiers in combination with SBS-PCM increased the averaged laser power by a **factor of >8**.
- **This laser is applicable to a diagnostic laser for ITER edge Thomson scattering system.**



# A single-stage diode-pumped Nd:YAG amplifier system at a 1 kilohertz-repetition-rate using a SBS-PCM.

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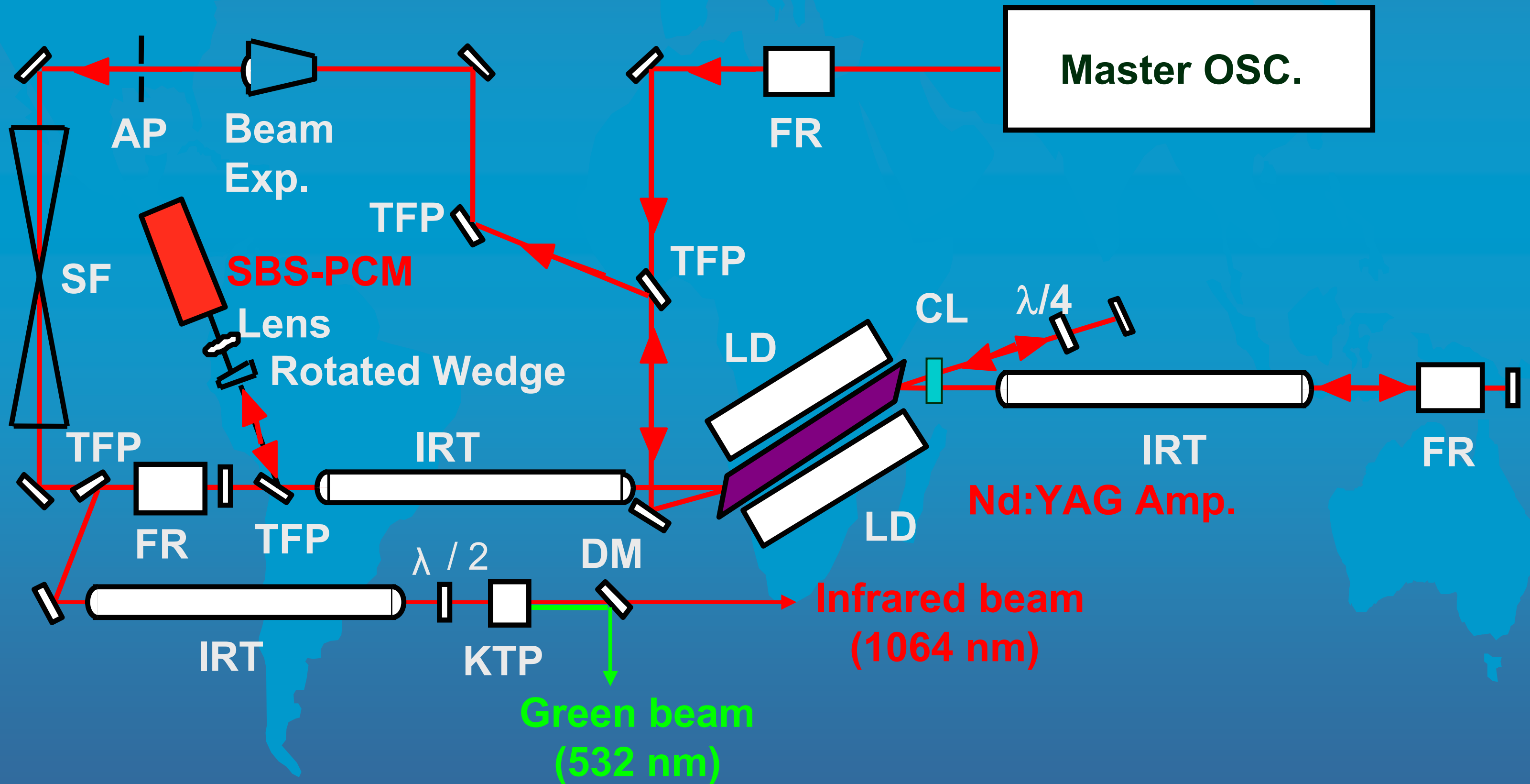
H.Kiriyama et al., Opt. Lett., 28(2003)1671-1673

We report on a high-average-power laser-diode (LD) pumped Nd:YAG master-oscillator-power-amplifier (MOPA) system with a minimum number of elements for the single multi-pass zigzag-slab amplifier-stage for pumping of a high-peak and high-average power Ti:sapphire laser system.



# 362 W average power operation with a single-stage diode-pumped Nd:YAG amplifier at a 1 kilohertz-repetition -rate using a SBS-PCM.

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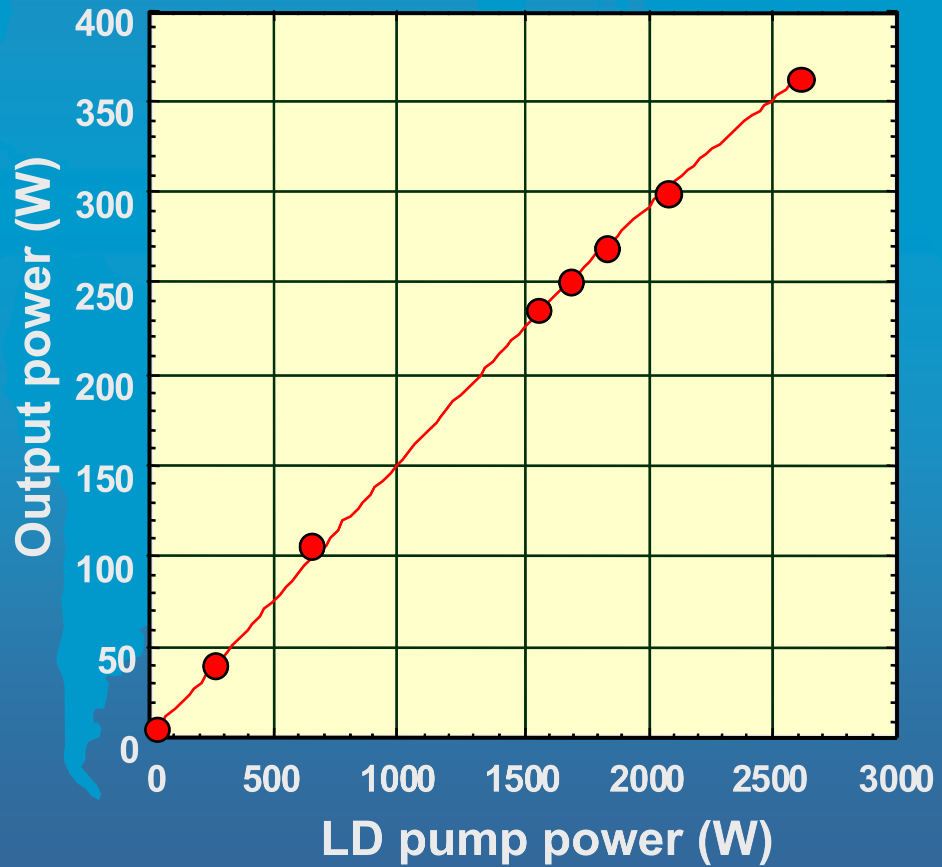
This phase conjugated system produces an average-power of 362 W at 1 kHz in a 30 ns pulse with an optical to optical efficiency of 14 %.

With an external KTP doubler, this system generates 132 W of green average-output-power at 1 kHz with a conversion efficiency of 60 %. To the best of our knowledge, these results represent the highest average-output-powers at both infrared and green wavelengths achieved in a single-amplifier-stage.



# Laser performance of 5 kW (1J / 5 kHz)YAG laser system for EUV lithography

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## Requirement for laser system

Output □1 - 3 J/pulse
Pulse width□1 - 10 ns
Repetition □5 - 20 kHz
Stability □± 0.3 %

## Basic concepts of ILE

Oscillator □Fiber laser
Main Amplifier□CW LD Pump Solid State Laser
Output:1J/pulse
Pulse width:1-10ns
Repetition:5kHz

See take by H.Fujita, Session 7 on Friday

# Main amplifier chain
# of high average power Nd:YAG laser

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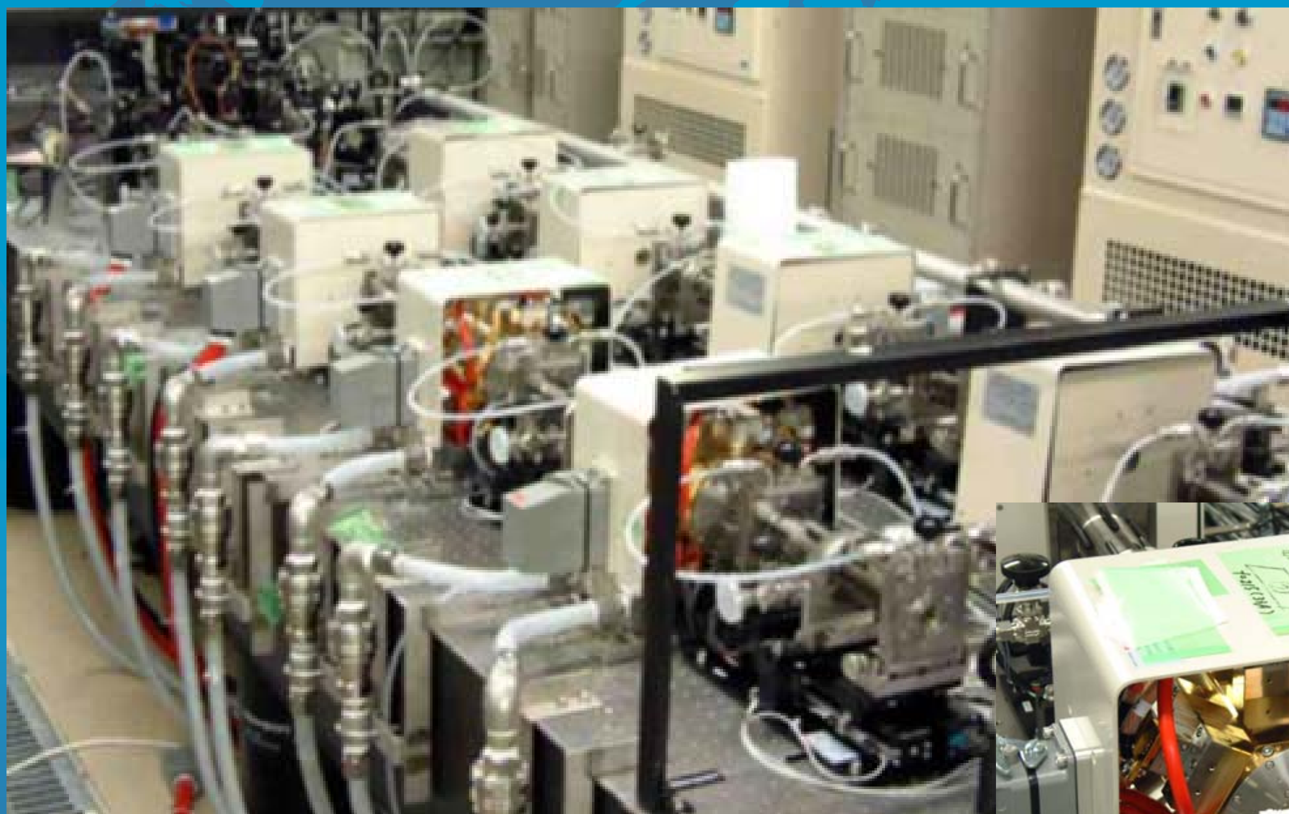

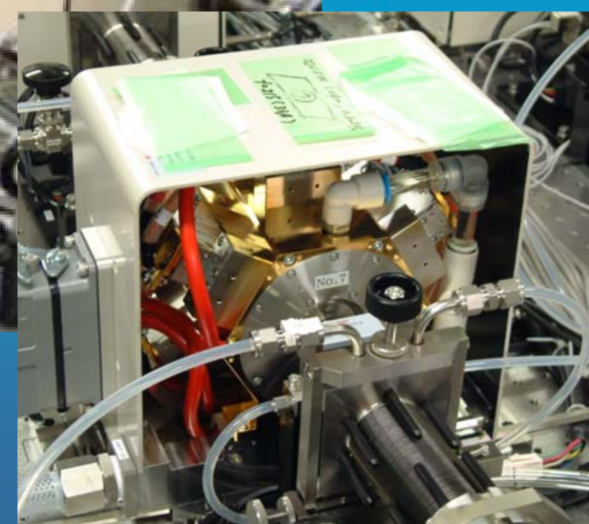

1 J, 3 ns, 5 kHz
5 kW Laser

# Optical layout of 5 kW (1J / 5 kHz)YAG laser system for EUV lithography

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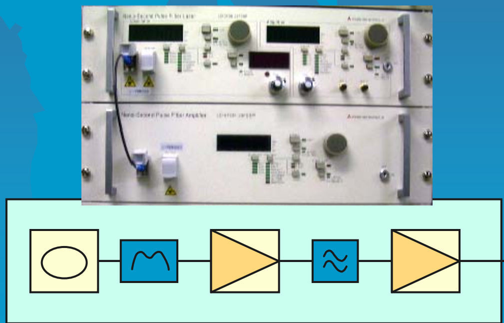
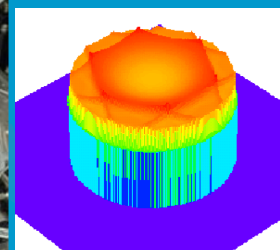
**Fiber Front-End**




**Main Amplifier Module**

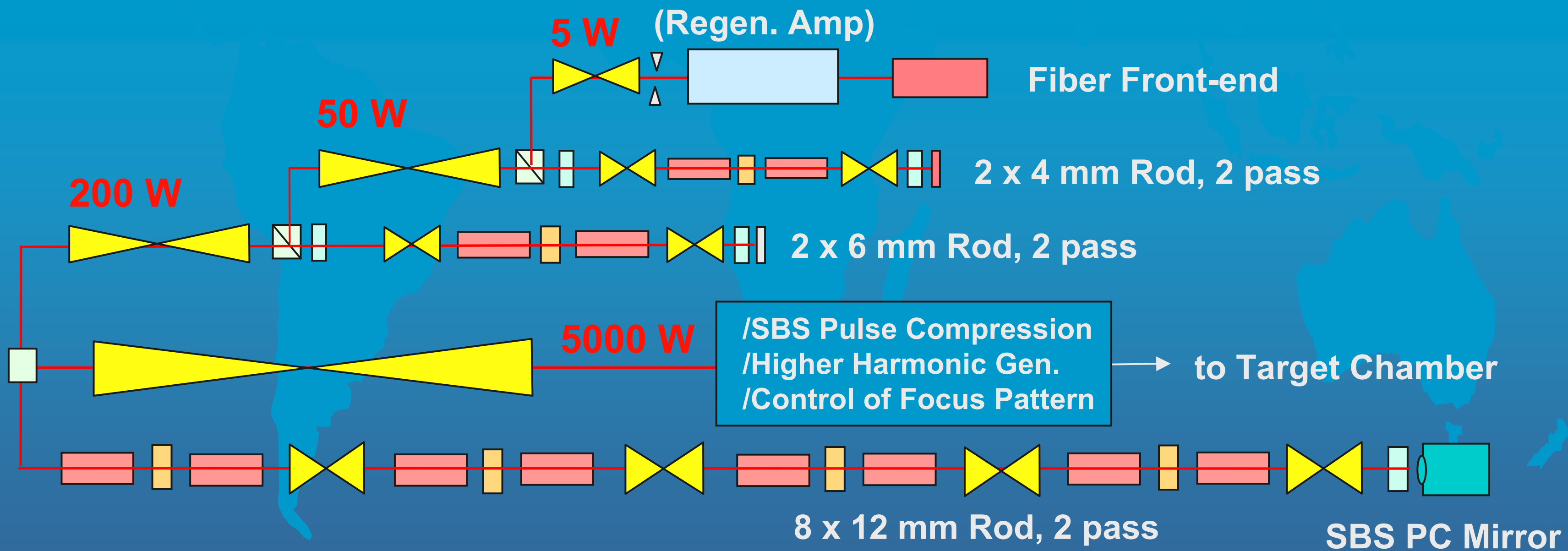
Total 3.6 kW LDs



Uniform Pumping

**SBS−PCM**

2 kW operation



# SBS-phase conjuation mirror by circulation of a coolant liquid.

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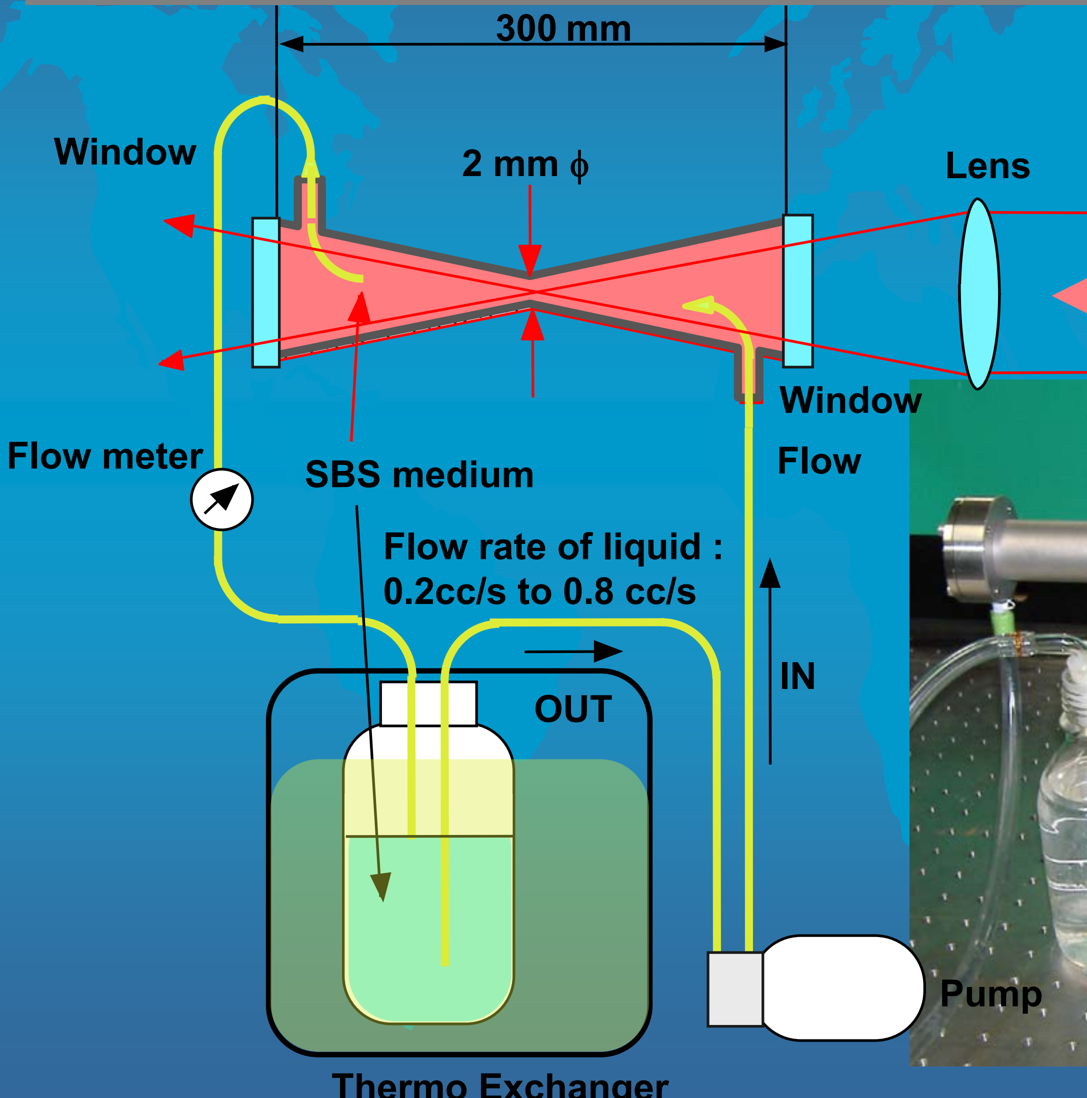
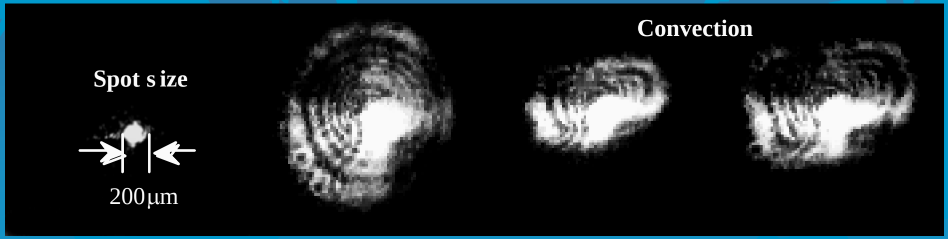



## The best solution for improvement in the fidelity and reflectivity of phase conjugation mirror is the adoption of an SBS cell moving the focal point by wedge plate rotation, and circulation of a coolant liquid.

ILE Osaka Univ.

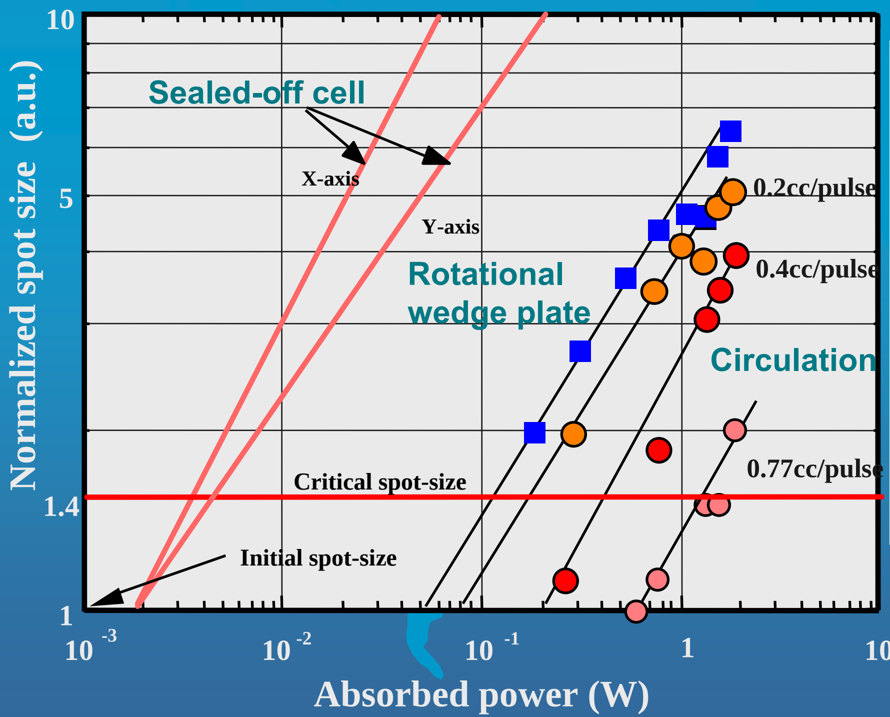
H.Yoshida et al. Rev. Laser Eng., No.29(2001)109.

No flowing




Time 0 s 3 s 6 s 9 s

Rapid flow of the SBS liquid in a cell reduces enlargement of the spot size less than critical value.




| Optical layout | SBS materials: Acetone | | SBS materials: Heavy fluorocarbon(FC-75) | |
|---|---|---|---|---|
| SBS reflectivity | 50% | 90% | 50% | 90% |
| Sealed-off cell | 20 mW | 100 mW | 10 W | 50 W |
| Rotational wedge plate (60 rpm) | 200 mW | 1 W | 100 W | 500 W |
| Circulation type (0.77cc/p) | 8 W | 40 W | 4 kW | 20 kW |

# Conclusions.

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Phase conjugation mirror with stimulated Brillouin scattering (SBS-PCM) is useful to compensate the wave-front distortion due to the thermally induced aberration and depolarization of average power solid-state lasers.

To achieve high power with a near-diffraction-limited beam, master-oscillator power-amplifier (MOPA) configurations demonstrated in which both liquid and solid Brillouin conjugators are used.

The capability of liquid SBS-PCM demonstrate up to 370 W of output power while keeping the near-diffraction beam quality.

↓

| | |
|---|---|
| FL pumped MOPA system | 373W(7.46J, 50Hz) |
| LD pump zig-zag YAG system | 362W(0.36J, 1 kHz) |

↓

Introduction of high power laser YAG system (5 kW) with SBS-PCM by circulation of a coolant liquid.

**Thank you very much for your attention !!**

# SBS reflectivity using a FC-75 liquid at a 2 kilohertz-repetition-rate.

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**YAG laser**
**Pulse width -15ns**
**Repitition -2 kHz**